

Noise Emission from InSb*

Abstract: This paper gives a new explanation of the low-field noise emission from InSb. Theoretical predictions and experimental measurements with a fine tungsten probe (10- μ m definition) show that there are very large fields at one corner of the cathode contact in the presence of a transverse magnetic field. Our experiments show that avalanching occurs near this point and the noise amplitude has a strong maximum there. In a longitudinal magnetic field all samples measured have shown inhomogeneities near the cathode contact, which are the source of noise.

Introduction

Microwave noise emission from InSb at low temperature in a magnetic field with low threshold fields of 50 V/cm or less was first observed by Buchsbaum, Chynoweth and Feldmann.¹ Since that time, the experiments have been repeated in the presence of transverse and longitudinal magnetic fields with similar but not identical results obtained in various laboratories. In early work in this laboratory we observed the onset of the noise phenomenon at roughly the same threshold field in both longitudinal and transverse magnetic fields, the noise occurring from frequencies of a few megahertz up into the millimeter wavelength range. However, one peculiarity which was noted by Eidson² was that with a longitudinal magnetic field the threshold electric field for onset of noise was dependent on the direction of the electric field, but with a transverse magnetic field it was not dependent on the direction of the electric field. It was also shown by Chynoweth et al.,³ that the threshold electric field tended to decrease with an increase of the cross section of the sample.

Earlier work by Larabee^{4,5} and others indicated strong noise emission at high electric fields where avalanching or hole injection was to be expected. Such phenomena can be well explained by the closely related electron-hole interaction theories of Kino and Burke,⁶⁻⁸ Suzuki,⁹ and Swartz and Robinson.¹⁰ The experimental observations of Burke⁸ show that, just above the threshold for growth, the gain is sufficient to give saturation of the gain mechanism and hence noise generation from shot noise excitation at the cathode.

* The research reported in this paper was supported partly by the U. S. Air Force Systems Command, Rome Air Development Center, Griffiss Air Force Base, New York, under Contract F 30602-68-C-0074, and by the National Science Foundation under Grant NSF GK-2175.

The authors are with the Department of Electrical Engineering, Stanford University, Stanford, California 94305.

Another well-documented explanation for noise emission from InSb is connected with piezoelectric interactions of acoustic waves with drifting electrons.¹¹⁻¹⁴ Such noise phenomena can certainly occur and be predicted in detail for long samples with the direction of electron drift in the [110] direction.

It is our contention in this paper, however, that neither of these effects can account for low-field emission from InSb in all cases. With a low electric field very few holes should be present, even in the presence of injection, because of strong hole trapping effects. If the sample were sufficiently short and not aligned in the best direction for strong acoustic interactions, the acoustic coupling would be too weak for strong noise generation. Typically, for lengths greater than 0.25 mm, the threshold for noise appears to be independent of length. This would certainly not be the case if acoustic interactions were the primary source of noise.

In this paper we offer a new explanation of the noise phenomenon which appears to be consistent with most of the experimental observations, and explains some of their inconsistencies and dependence on the nature of the contacts. We suggest that the key to the phenomenon lies in the nature of the effects in a transverse magnetic field. In this situation the dc field distribution is radically distorted because of the shorting out of the Hall field at the cathode contact, and the dc electric field becomes very large (theoretically infinite) at one corner of the contact. Consequently, avalanching takes place at this corner and noise generation initially occurs at the same point. Experimental observation with a movable fine tungsten probe bears out the theory. Preliminary observations of infrared emission from the sample also tend to confirm the avalanching hypothesis.

We first describe a simple dc theory which demonstrates the origin of the high-field region near one corner of the cathode. We then describe the experimental results that confirm the avalanching hypothesis. Finally, we shall discuss the nature of the phenomenon in the presence of a longitudinal magnetic field.

DC field theory

We determine the electric field in a crystal placed in a transverse magnetic field by using a Schwarz-Christoffel conformal transformation technique due to Wick.¹⁵ The results for a sample with its length much greater than its width have been examined in detail by Turner.¹² To simplify the analysis we assume from the start that the sample is semi-infinite.

The conformal mappings are illustrated in Fig. 1. The Z plane contains the semi-infinite sample with the cathode at $x = 0$. The boundary conditions are

$$\mathbf{E} = (E_x, 0) \quad \text{at } x = 0, \quad (1)$$

$$\mathbf{v} = (v_x, 0) \quad \text{at } y = 0, h, \quad (2)$$

which, from the equation of motion, imply that

$$\frac{E_y}{E_x} = \tan \theta_H = -\mu B \quad \text{at } y = 0, h, \quad (3)$$

where θ_H is the Hall angle and $\mathbf{B}_T = -B\hat{z}$ is the transverse magnetic field.

We transform to a plane Z' in which the transformed diode is a semi-infinite parallelepiped with a corner angle θ_H , as illustrated in Fig. 1. With the boundary conditions given, the solution in the Z' plane requires the electric field to be uniform and parallel to the x' axis. Thus it follows that

$$\begin{aligned} \frac{dZ'}{dZ} &= \frac{\partial x'}{\partial x} + i \frac{\partial y'}{\partial x} = \frac{\partial x'}{\partial x} - i \frac{\partial x'}{\partial y} \\ &= -(E_x - iE_y) \Rightarrow -\frac{dZ'}{dZ} = E^*. \end{aligned} \quad (4)$$

The transformation from the Z' plane to the Z plane is obtained by mapping the interior of the diode into the W upper half-plane using a Schwarz-Christoffel transformation, and following this by a second mapping of W into Z' . The first transformation is¹⁶

$$W = \cosh \left(\frac{\pi Z}{h} \right). \quad (5)$$

The second transformation is given by the relation

$$Z' = Z'_0 + A' \int (W - 1)^{-\frac{1}{2}(1+l)} (W + 1)^{-\frac{1}{2}(1-l)} dW, \quad (6)$$

where

$$\theta_H = l\pi/2. \quad (7)$$

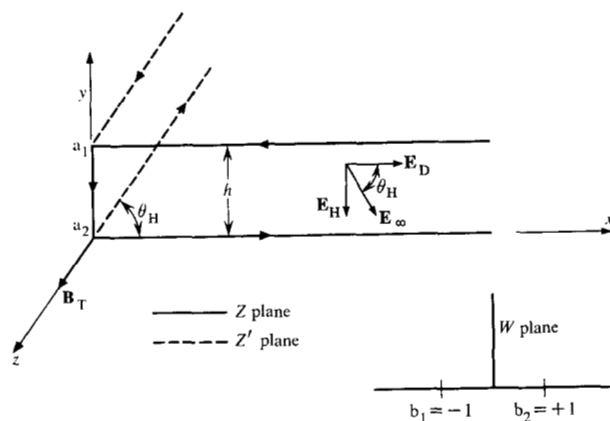


Figure 1 Conformal mappings taking the Z plane into the W plane, followed by a similar transformation to Z' .

Then, substituting Eq. (5) into Eq. (6) and using Eq. (4), we obtain the electric field at the cathode of n-InSb:

$$\begin{aligned} E^* &= E_\infty^* \left[\cosh \left(\frac{\pi Z}{h} \right) - 1 \right]^{-\frac{1}{2}(1-l)} \\ &\quad \times \left[\cosh \left(\frac{\pi Z}{h} \right) + 1 \right]^{-\frac{1}{2}(1+l)} \sinh \left(\frac{\pi Z}{h} \right), \end{aligned} \quad (8)$$

where

$$E_\infty = E_D + iE_H. \quad (9)$$

Here E_∞ represents a vector in the complex plane with real and imaginary parts (component magnitudes) given respectively by E_D , the drift field, and E_H , the Hall field.

We are interested in the field near the corner $x = 0$, $y = h$. Thus we let $Z = ih + z$, where $|z|/h \ll 1$ and $z = re^{i\theta}$, and expand Eq. (8) to give the equation

$$E_c \simeq E_\infty \left(\frac{2h}{\pi|z|} \right)^l \quad (10)$$

where E_c is the field near the corner. Thus $|E_c| \rightarrow \infty$ as $|z| \rightarrow 0$, and the field becomes infinite at the corner. The nature of the field near the corner is clarified by writing it in polar coordinates, which results in the relations

$$E_\theta \simeq -\left(\frac{2}{\pi} \right)^l E_\infty \left(\frac{h}{r} \right)^l \quad (11)$$

and

$$E_r \simeq -\left(\frac{2}{\pi} \right)^l \left(\frac{h}{r} \right)^l E_H \theta (1 - l), \quad (12)$$

where in InSb

$$E_\infty = \sqrt{E_D^2 + E_H^2} \simeq E_H.$$

Near the corner the electrostatic potential is

$$\Phi_c = -\operatorname{Re} \int E_c^* dz, \quad \text{or}$$

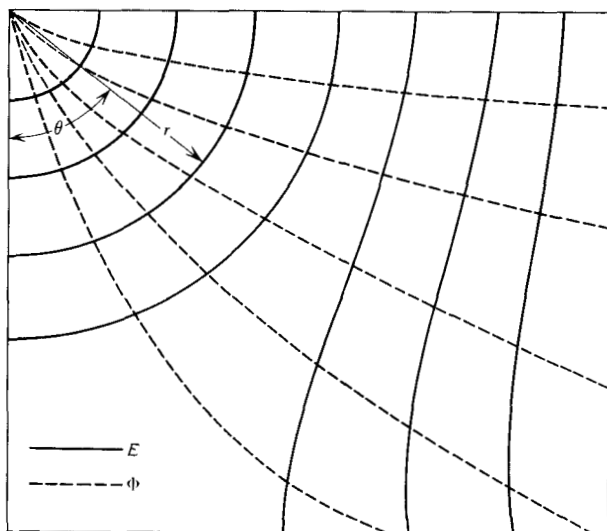
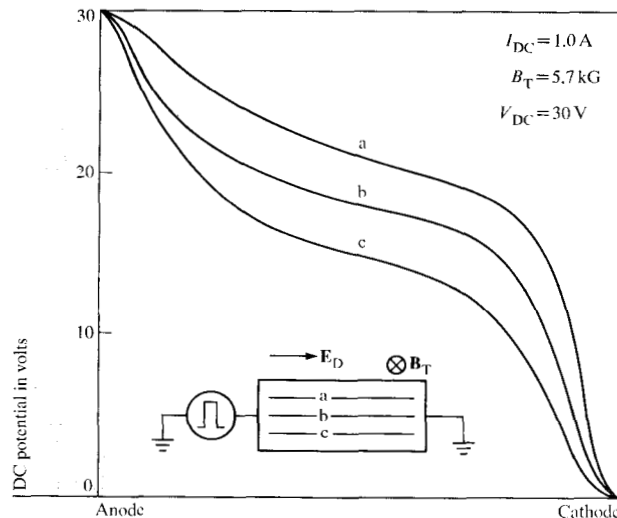


Figure 2 The approximate field lines and equipotentials near the cathode. The electric field is circular about the high-field corner.

Figure 3 DC potential vs. position, indicating the field symmetry and high fields near the contacts.



$$\Phi_0 \simeq + \left(\frac{2}{\pi}\right)^l \left(\frac{r}{h}\right)^{1-l} E_H h \theta, \quad (13)$$

where it has been assumed in Eqs. (10) to (13) that $l \simeq 1$, which is a good approximation for $B \geq 1$ kG. In Fig. 2 a sketch of the field lines and the equipotentials is given. Note that

$$\frac{E_r}{E_\theta} \simeq (1-l)\theta \ll 1 \text{ for } B \geq 1 \text{ kG.}$$

Thus, near the corner the electric field lines are nearly circular. It should also be observed that for $\mu B \gg 1$, $1-l \ll 1$ and the factor $(r/h)^{1-l}$ in Eq. (13) is a slowly varying function for all but very small values of r . For instance, for $B = 2$ kG and $\mu B = 10$, we have $1-l = 0.06$; then $1\mu\text{m}$ from the corner the potential is already 75% of its value at $r = 200\mu\text{m}$. Thus the theory predicts that the potential rises to essentially its full value in a distance which may be small compared with an electron mean-free path in InSb. In these same regions the field can be extremely high.

Experimental results

A number of experiments have been performed which substantiate this theory and lead to the conclusion that avalanching occurs in the high-field corner. The experimental apparatus consists primarily of a micromanipulator which is capable of placing a $10\mu\text{m}$ -diameter tungsten probe on the surface of an InSb sample with relative locational errors of less than $25\mu\text{m}$. The probing is done with the sample submerged in liquid nitrogen and placed between the poles of an electromagnet. The samples used typically had dimensions $0.1 \text{ cm} \times 0.1 \text{ cm} \times 1.0 \text{ cm}$, mobilities greater than $5 \times 10^5 \text{ cm}^2/\text{V}\cdot\text{sec}$ and carrier densities in the range 1×10^{14} to $5 \times 10^{14} \text{ cm}^{-3}$.

A plot of potential vs. position is given in Fig. 3. This plot was made before it was realized that under these conditions avalanching was taking place at one corner. However, the field symmetry about the sample diagonal and the high-field regions near the contacts are apparent. In Fig. 4 the potentials at several points 5 mils from the cathode are given as a function of sample current. Average transverse fields can be calculated from changes in potential with position. The average longitudinal field can be calculated by dividing the potential by the distance from the cathode (5 mils). For instance, 5 mils down from the top side of the sample (the second curve from the top) and 5 mils from the cathode the measured transverse average field is 210 V/cm at 1.0 ampere. The value calculated from Eq. (10) is 260 V/cm . Alternatively, the measured potential is 8.6 V and the potential calculated from Eq. (13) is 10.8 V . Thus the measured values agree with this simple theory to within 20%. This is reasonable accuracy since a 20% uncertainty in position is equivalent to 1 mil.

In Fig. 4, it can also be seen that there are negative resistance regions near the middle of the cathode: when the total current through the sample is varied the voltage initially increases and then decreases. A reasonable explanation of this effect is that avalanching is occurring in this region. Near the cathode the carrier velocity is nearly parallel to the contact, since the Hall field is shorted out. Thus the avalanche develops at the high-field corner and continues across the sample, almost parallel to the

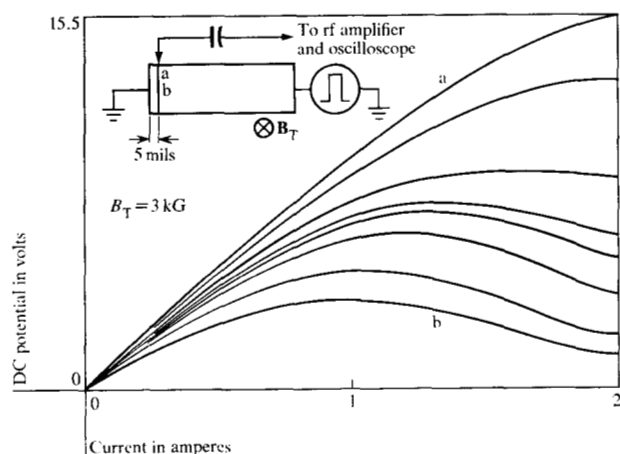


Figure 4 Potential vs. sample current 5 mils from the cathode. The lower curves show negative resistance regions.

cathode to the low-field side. Further investigation showed that the rf noise emission has a strong maximum near the high-field corner and that it decreases in amplitude more rapidly in the longitudinal direction than in the transverse direction. This result is shown in Fig. 5. In Fig. 6 are results similar to those in Fig. 4, taken 1 mil from the high-field corner. The position is estimated to be accurate to ± 0.5 mil. On each curve, corresponding to different magnetic fields, the noise threshold is marked. The negative resistance effect is seen to be stronger near the corner. Moreover, in each case the noise threshold occurs approximately at the point where the local differential resistivity begins to decrease, i.e., at the point where avalanching begins. Furthermore, the average field between the probe point and the cathode, at threshold, is greater than 1000 V/cm. The theory would indicate that the maximum value of the field may be considerably higher than this value.

Conclusions

The results given lead us to the conclusion that, in a transverse magnetic field, the electric fields in one corner of the cathode of an InSb sample are large enough to cause impact ionization. The measured average local fields, as large as 2500 V/cm, are well above the field necessary for electron avalanche in InSb. Furthermore, the local I - V curves indicate that the negative resistance region occurs well within the sample and that its location is a function of the field value. The fact that no noise is measured before the local resistance changes also suggests a causal relation between noise emission and avalanching. The rapid attenuation of the noise amplitude with distance, shown in Fig. 5, may be attributed to rapid hole trapping increased by the strong Suhl effect.¹⁷ The constant background level is just that due to ohmic

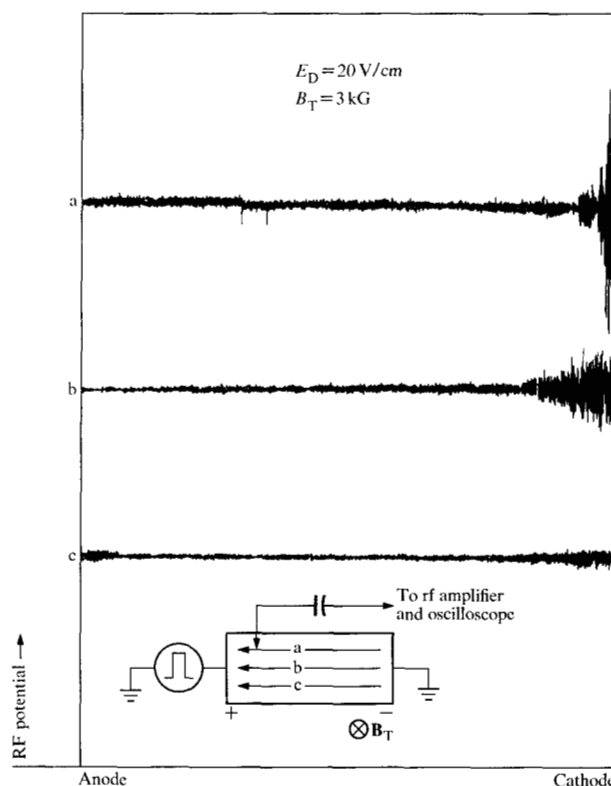
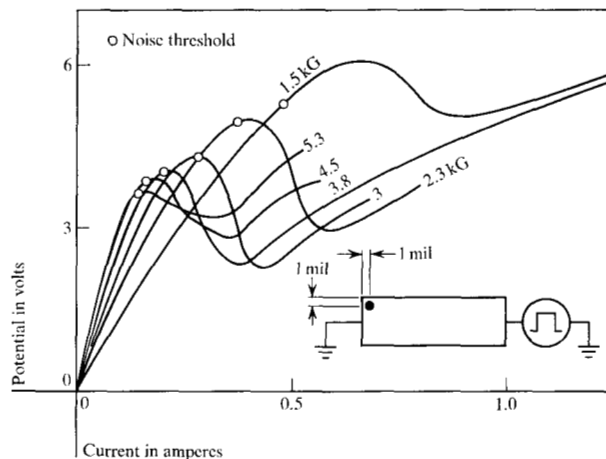


Figure 5 Noise emission vs. position, showing noise peak near the cathode.

Figure 6 Potential vs. current at several magnetic field strengths. The noise thresholds are indicated where they occur (near the avalanche threshold).



conduction of the noise signal generated at the cathode and is easily detectable at the anode.

Treating the high-field region as a noise source leads to other implications. Route¹⁸ has detected noise in InSb on an acoustic transducer; this noise appears to increase radically in the region where avalanching would

be expected to occur. The avalanche noise could be coupled to an acoustic disturbance by either piezoelectric coupling or by the change in volume associated with the creation of electron-hole pairs.

Experiments performed in a longitudinal magnetic field indicate that noise emission also originates at the cathode. However, unlike the transverse magnetic field case, the point of maximum noise emission does not change position when the magnetic field is reversed. In all the samples we have measured the noise emission appears to be associated with sample or contact defects. At the emission centers the dc field is very large and it would appear that the defects give rise to electric field components which are perpendicular to the magnetic field. Moreover, prolonged probing of a sample introduces more defects and the noise threshold fields are decreased.

It should also be remarked that, with a transverse field, large fields occur at the anode. However, it would not be expected that an electron avalanche would have enough space to become fully developed. Only relatively small increases in emitted noise have been observed at the anode.

Finally, from the nature of the theory given it would be expected that, whatever the shape of the sample, similar high-field regions would be present and hence avalanching and noise emission would occur. With a longitudinal magnetic field only very small defects in the contact, or chips on the surface of the sample, would be sufficient to give rise to this noise phenomenon. In this case it would follow from Eqs. (11) and (12) that the high field at this point would tend to be proportional to the width of the sample, and hence the threshold field for noise would decrease with an increase in sample

width. Thus the theory given here tends to explain, at least qualitatively, many of the observations made of the low-field noise generation in InSb.

References

1. S. J. Buchsbaum, A. G. Chynoweth and W. L. Feldmann, *Appl. Phys. Letters* **6**, 67 (1965).
2. J. C. Eidson and G. S. Kino, *Appl. Phys. Letters* **8**, 183 (1966).
3. A. G. Chynoweth, S. J. Buchsbaum and W. L. Feldmann, *J. Appl. Phys.* **37**, 2922 (1966).
4. R. D. Larrabee, *Bull. Am. Phys. Soc.* **9**, 258 (1964).
5. R. D. Larrabee and W. A. Hicinbotham, Jr., *Proc. Symposium on Plasma Effects in Solids*, Paris, France (1964).
6. G. S. Kino, *Appl. Phys. Letters* **12**, 312 (1968).
7. B. E. Burke and G. S. Kino, *Appl. Phys. Letters* **11**, 310 (1968).
8. B. E. Burke, Ph.D. Thesis, Microwave Laboratory Report No. 1738, Stanford University.
9. T. Suzuki, *J. Phys. Soc. Japan* **21**, 2000 (1966).
10. G. A. Swartz and B. B. Robinson, *Appl. Phys. Letters* **9**, 232 (1966).
11. G. S. Kino and R. K. Route, *Appl. Phys. Letters* **11**, 312 (1967); R. K. Route and G. S. Kino, *Appl. Phys. Letters* **14**, 97 (1969); and R. K. Route and G. S. Kino, *IBM J. Res. Develop.* **13**, 507 (1969, this issue).
12. C. W. Turner, *J. Appl. Phys.* **39**, 4246 (1968).
13. M. Kikuchi, *Japan. J. Appl. Phys.* **5**, 1259 (1966).
14. C. Hammar and P. Weissglas, *Appl. Phys. Letters* **13**, 219 (1968).
15. R. F. Wick, *J. Appl. Phys.* **25**, 741 (1954).
16. For example, see P. M. Morse and H. Feshbach, *Methods of Theoretical Physics*, McGraw-Hill Book Co., Inc., New York 1953, p. 443.
17. W. Shockley, *Electrons and Holes in Semiconductors* D. Van Nostrand Co., Inc., New York 1950, p. 326.
18. R. K. Route, private communication.

Received April 11, 1969